Optical/IR Stellar Interferometry

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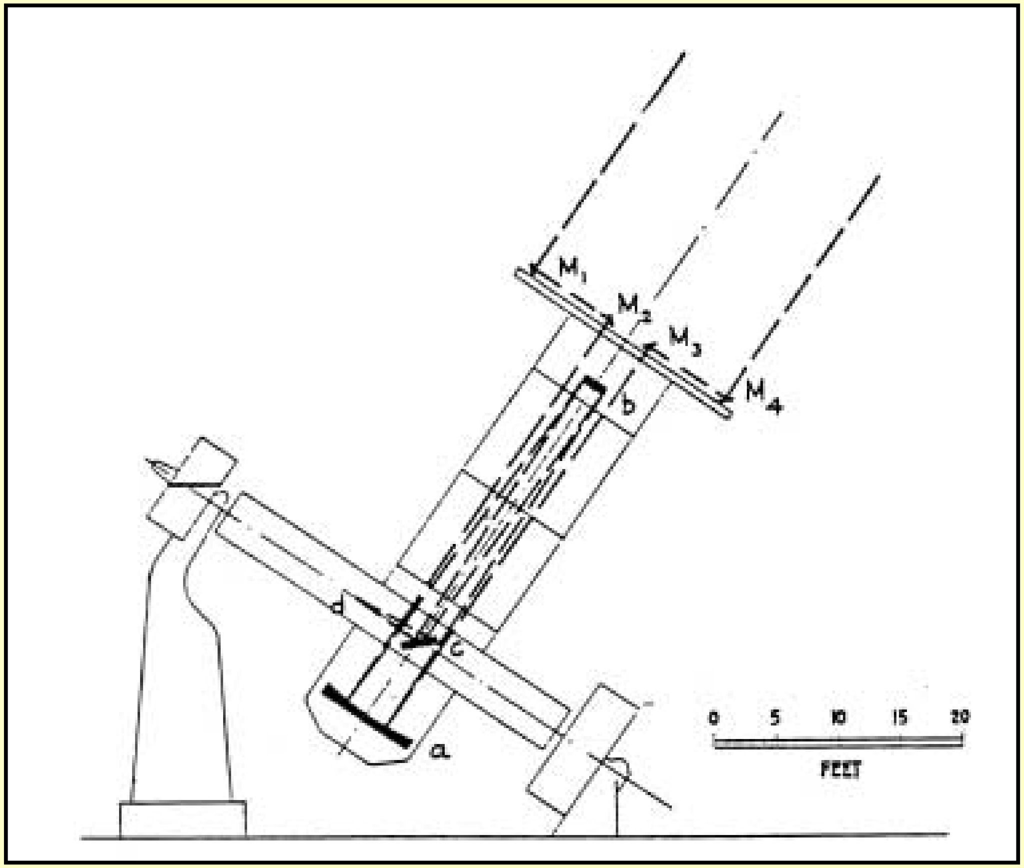
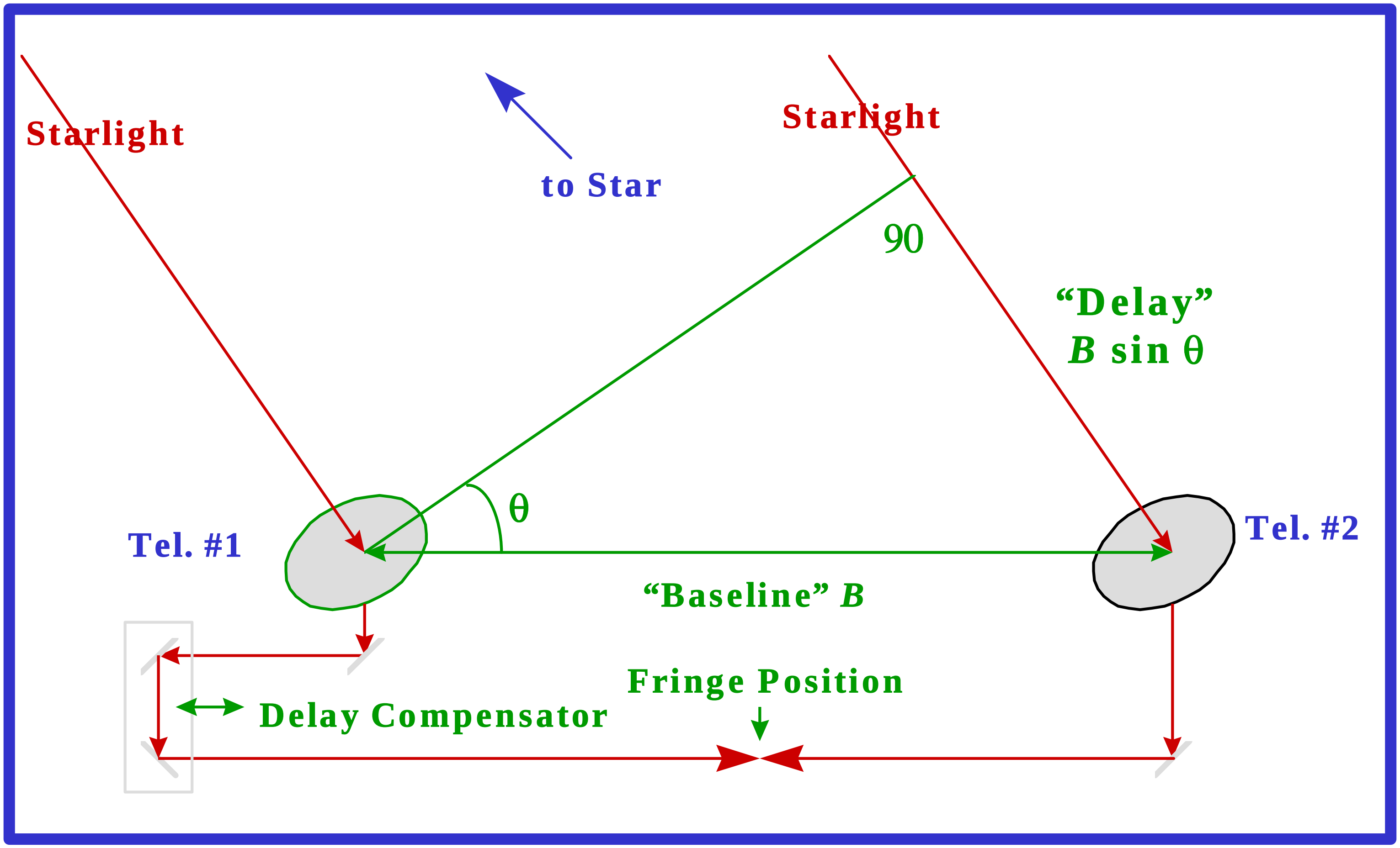
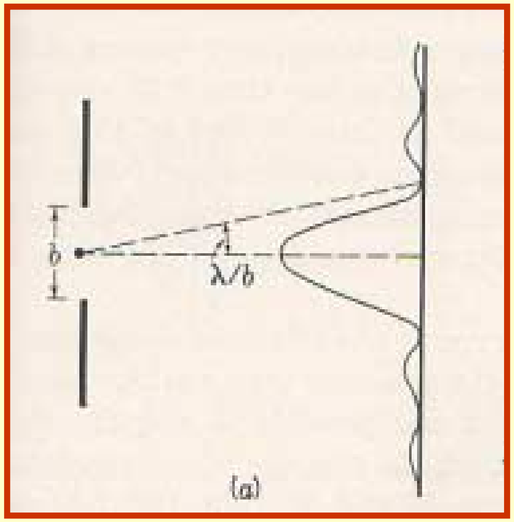


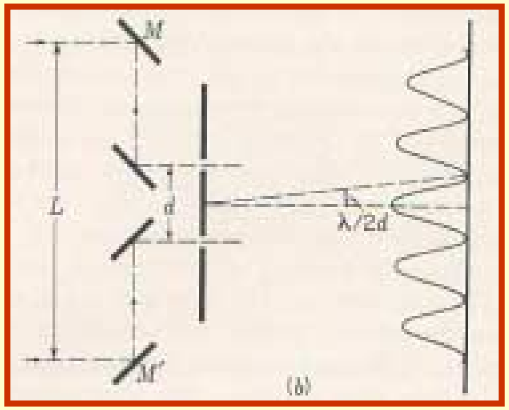
Basic Long-Baseline Interferometer



Michelson's Stellar Interferometer

Young's Double Slit Fringes





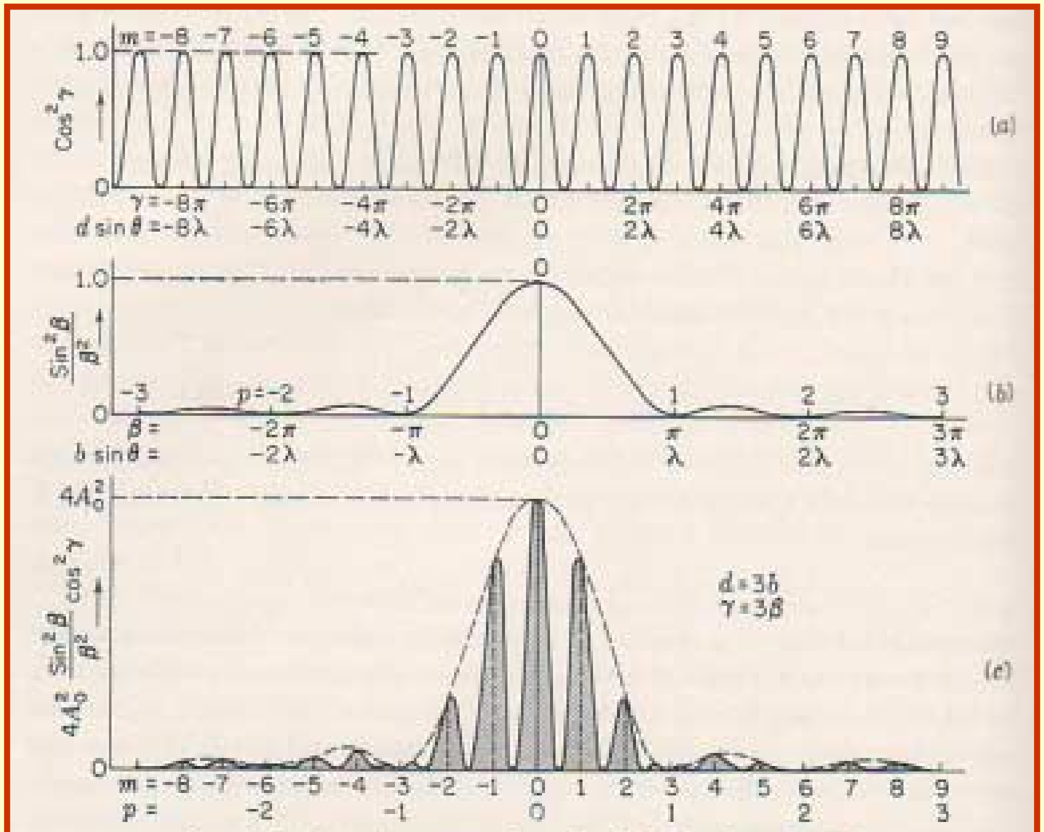


FIG. 16D. Intensity curves for a double slit where $d = 3b$.

"Visibility" – The Basic Observable

$$V(B) = \frac{\{I_{max} - I_{min}\}}{\{I_{max} + I_{min}\}}$$

For excellent background development, see the tutorial articles by A.F. Boden, W.A. Traub and others in <u>Principles of Long Baseline Stellar Interferometry</u>, Course notes from the 1999 Michelson Summer School ed. by P.R. Lawson.

Visibility Relation for Single Stars

$$V^2 = \{2[J1(\pi\Theta B/\lambda)]/[\pi\Theta B/\lambda]\}^2$$

Θ = *Angular Diameter*
B = *Baseline*
λ = *Wavelength*

Visibility Relation for Double Stars

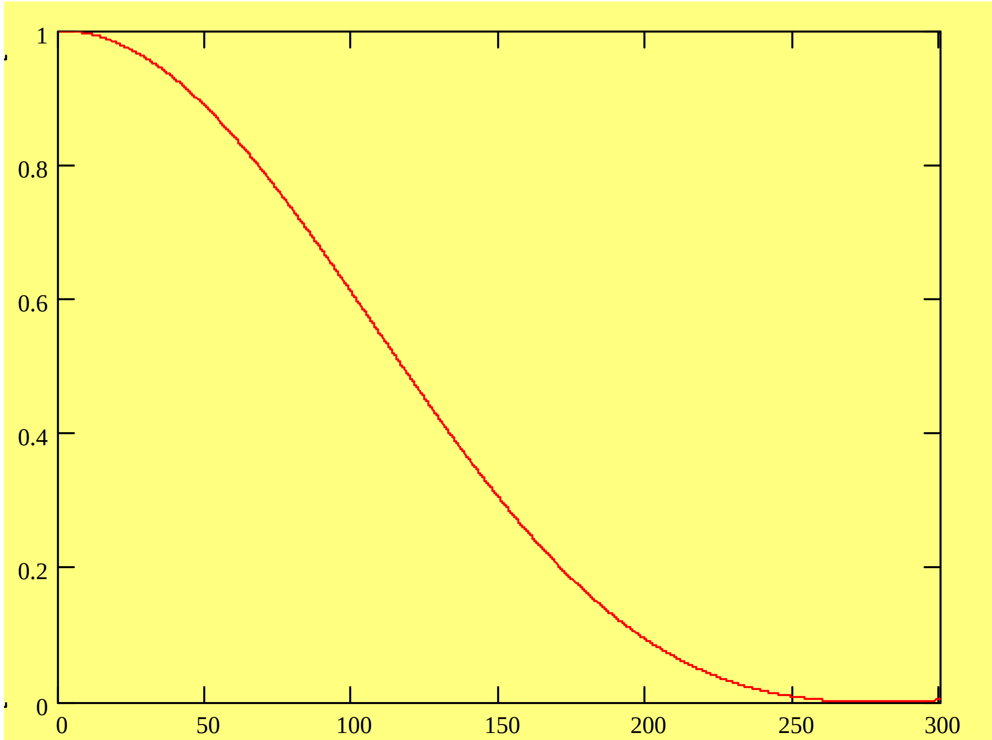
$$V^2 = [1+\beta]^{-2}\,[\beta^2 V_1(B)^2 + V_2(B)^2 + 2\beta V_1(B) V_2(B)\,\mathrm{Cos}(2\pi B\rho\,\mathrm{Cos}\theta_p\,/\lambda)]$$

β = *Brightness ratio (primary/secondary)*
ρ = *Angular separation*
θ_p = *Projection angle onto baseline* **B**

Effect of Increasing α

α = 5.0 mas

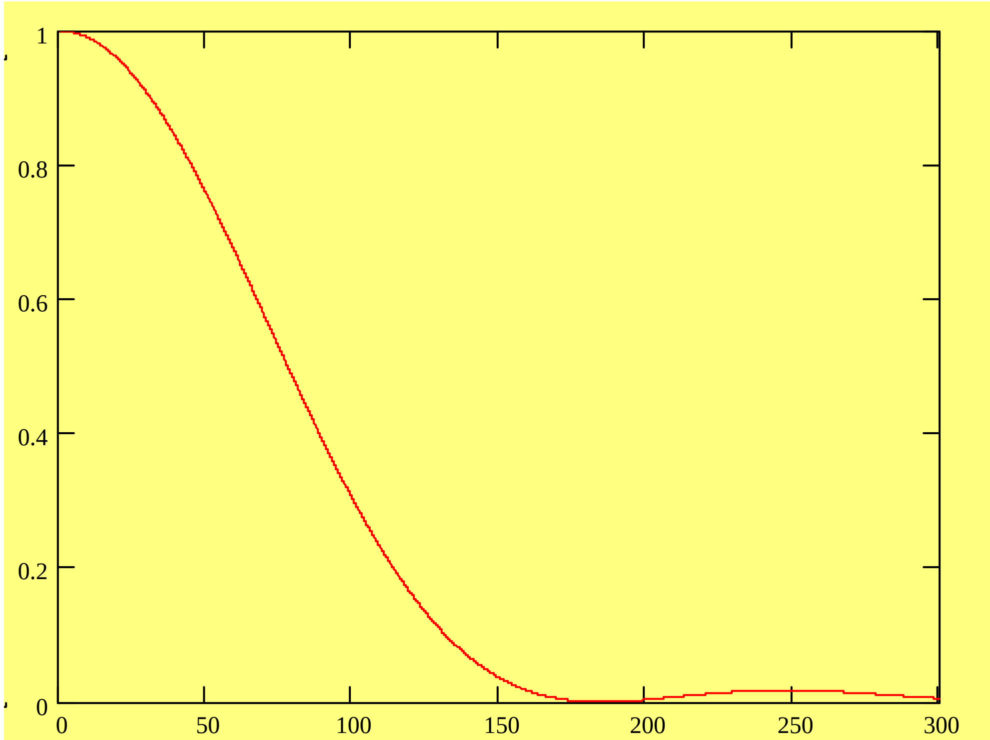
Visibility ^{2}



Baseline (meters)

Effect of Increasing α

α = 5.0 mas



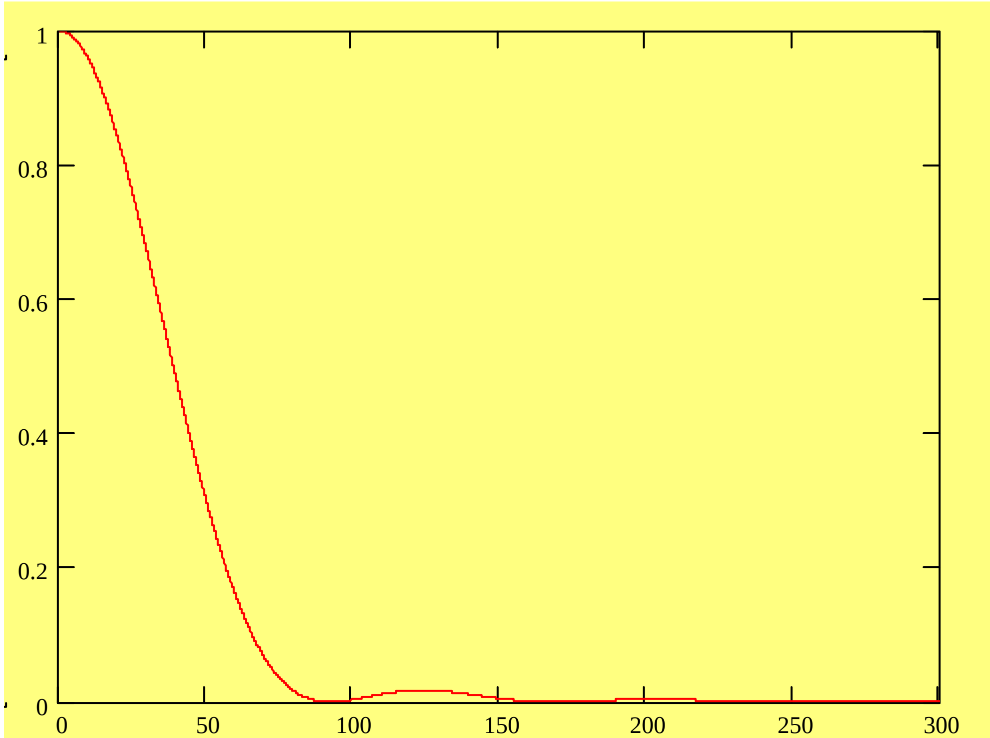
Visibility ^{2}

Baseline (meters)

Effect of Increasing α

α = 5.0 mas

Visibility ^{2}

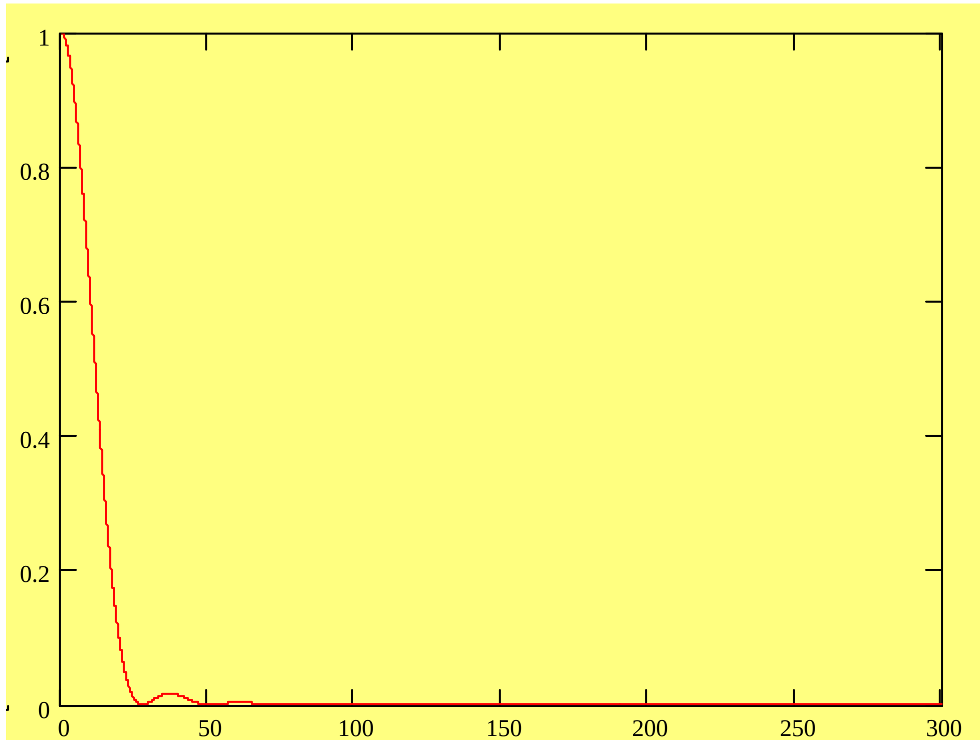


Baseline (meters)

Effect of Increasing α

***α* = 5.0 mas**

Visibility ^{2}



Baseline (meters)

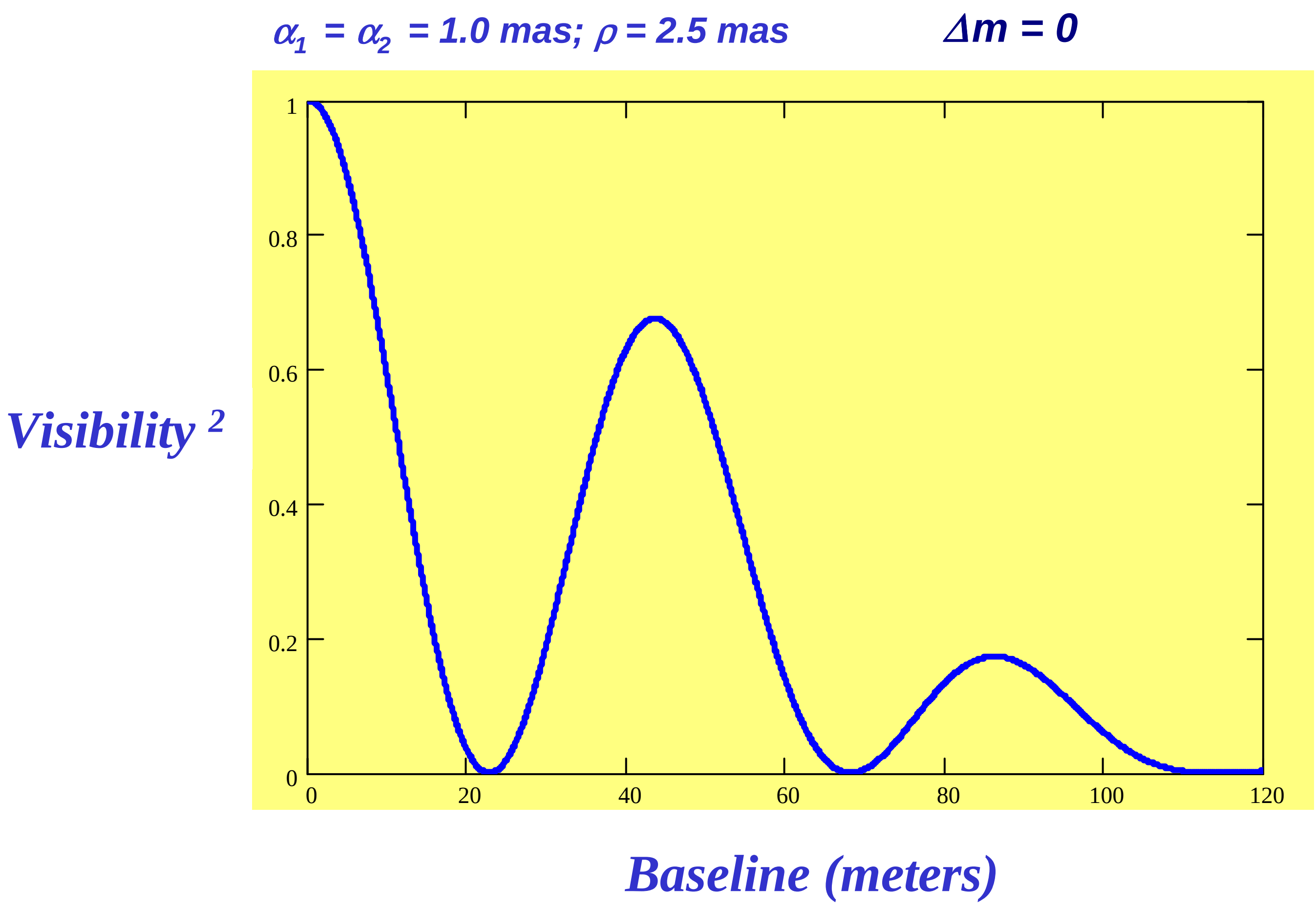
Effect of Increasing Δm

$\alpha_1 = \alpha_2 = 1.0$ mas; $\rho = 2.5$ mas

Visibility ^{2}

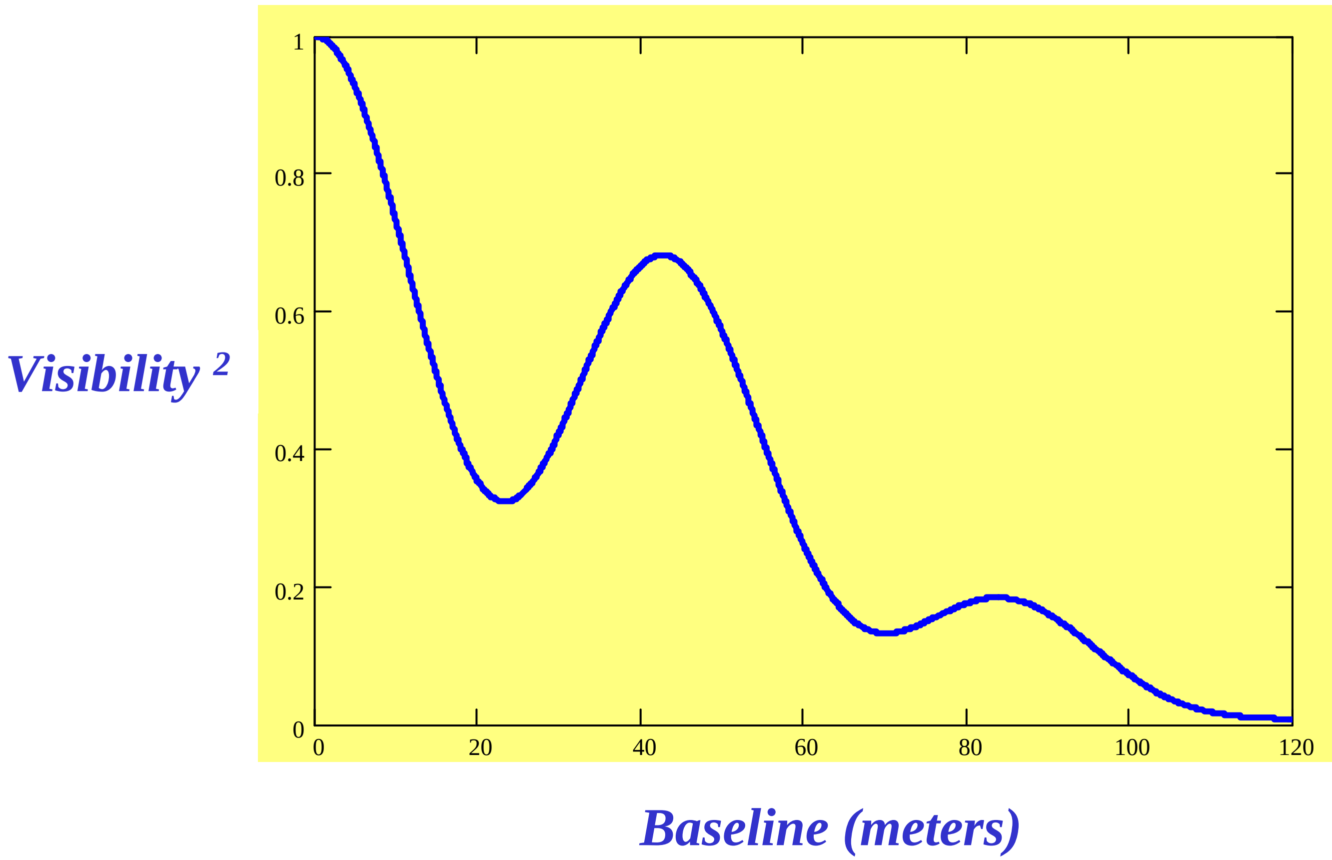
Baseline (meters)

Effect of Increasing Δm



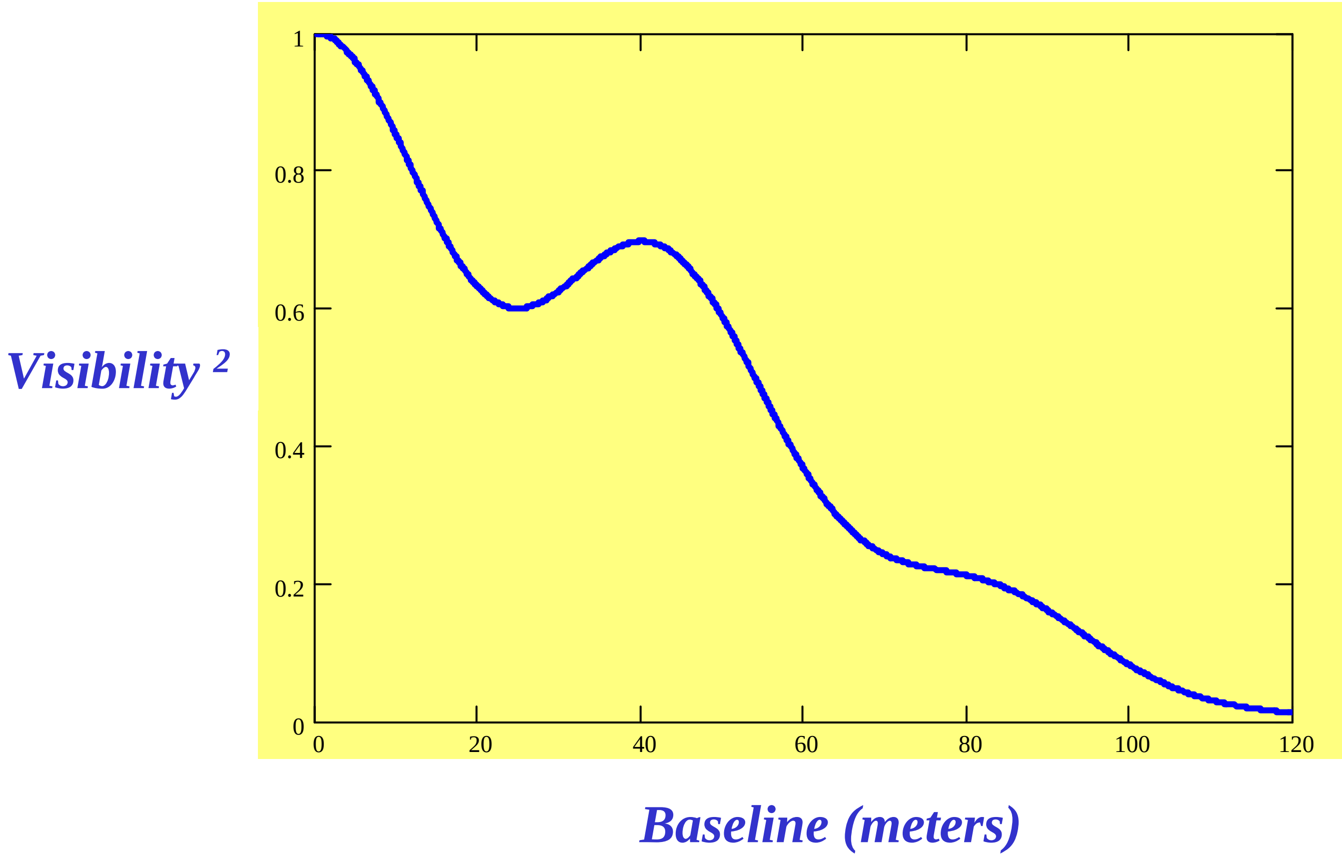
Effect of Increasing Δm

$\alpha_1 = \alpha_2 = 1.0$ mas; $\rho = 2.5$ mas $\Delta m = 1.5$



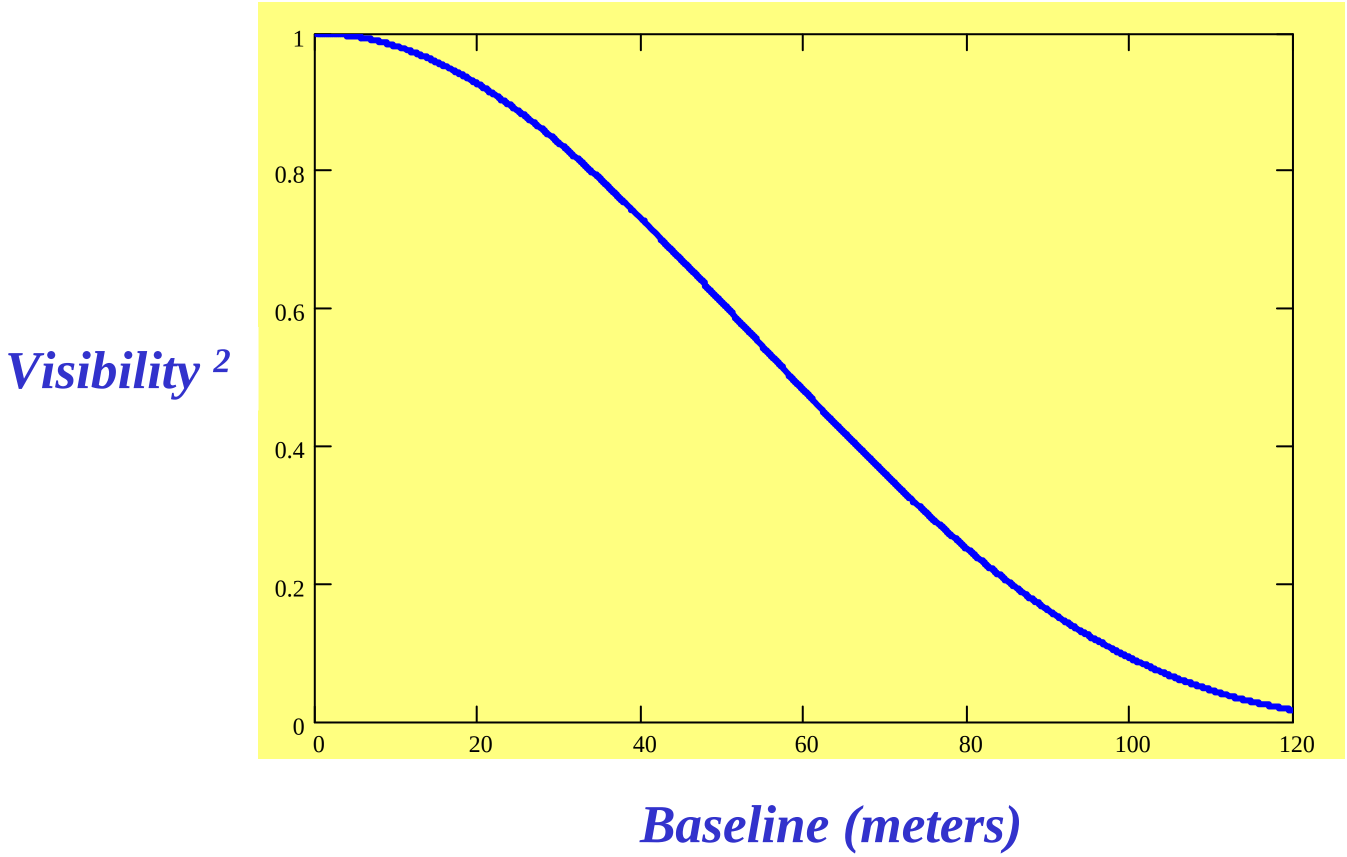
Effect of Increasing Δm

$\alpha_1 = \alpha_2 = 1.0$ mas; $\rho = 2.5$ mas **$\Delta m = 2.5$**



Effect of Increasing Δm

$\alpha_1 = \alpha_2 = 1.0$ mas; $\rho = 2.5$ mas $\Delta m = 10$



Effect of Increasing ρ

$\alpha_1 = \alpha_2 = 1.0$ mas; $\Delta m = 0$

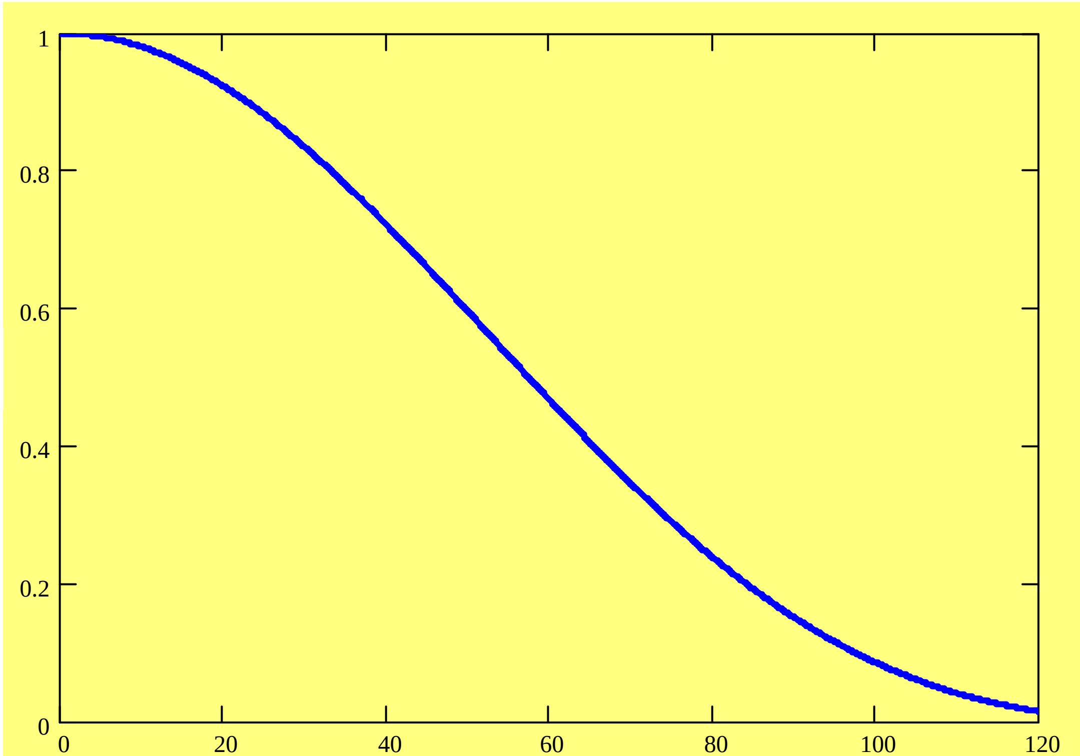
Visibility ^{2}

Baseline (meters)

Effect of Increasing ρ

α_1 = α_2 = 1.0 mas; Δm = 0

ρ = 0.1 mas



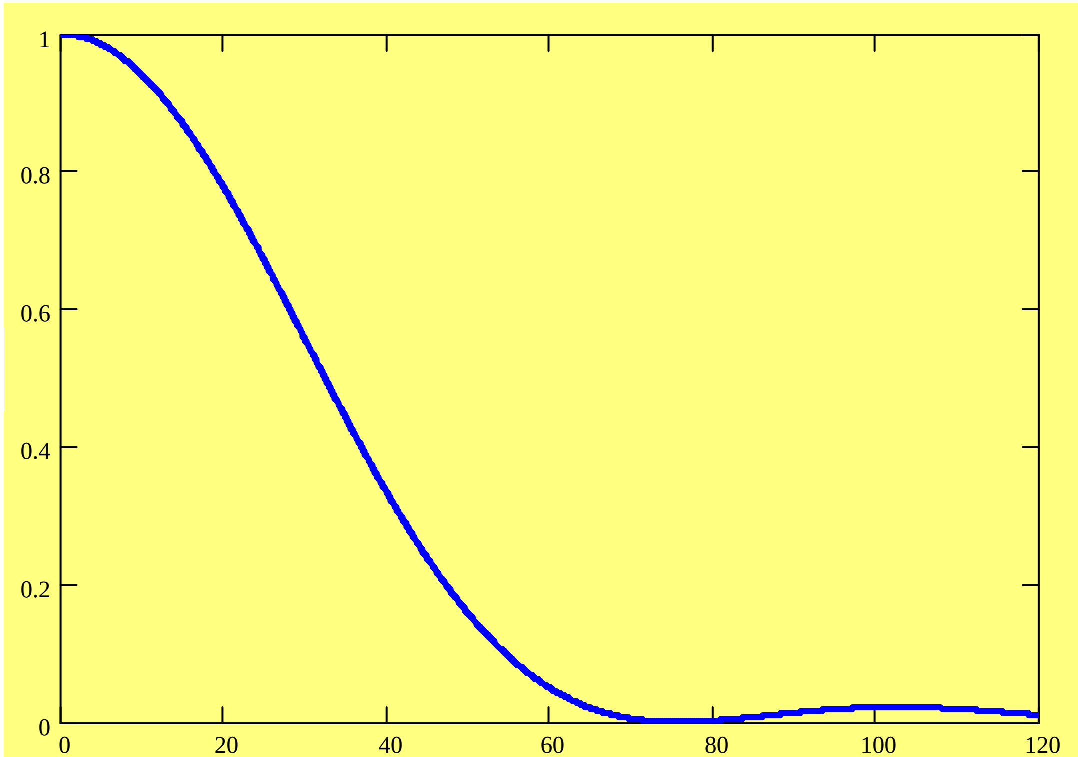
Visibility ^{2}

Baseline (meters)

Effect of Increasing ρ

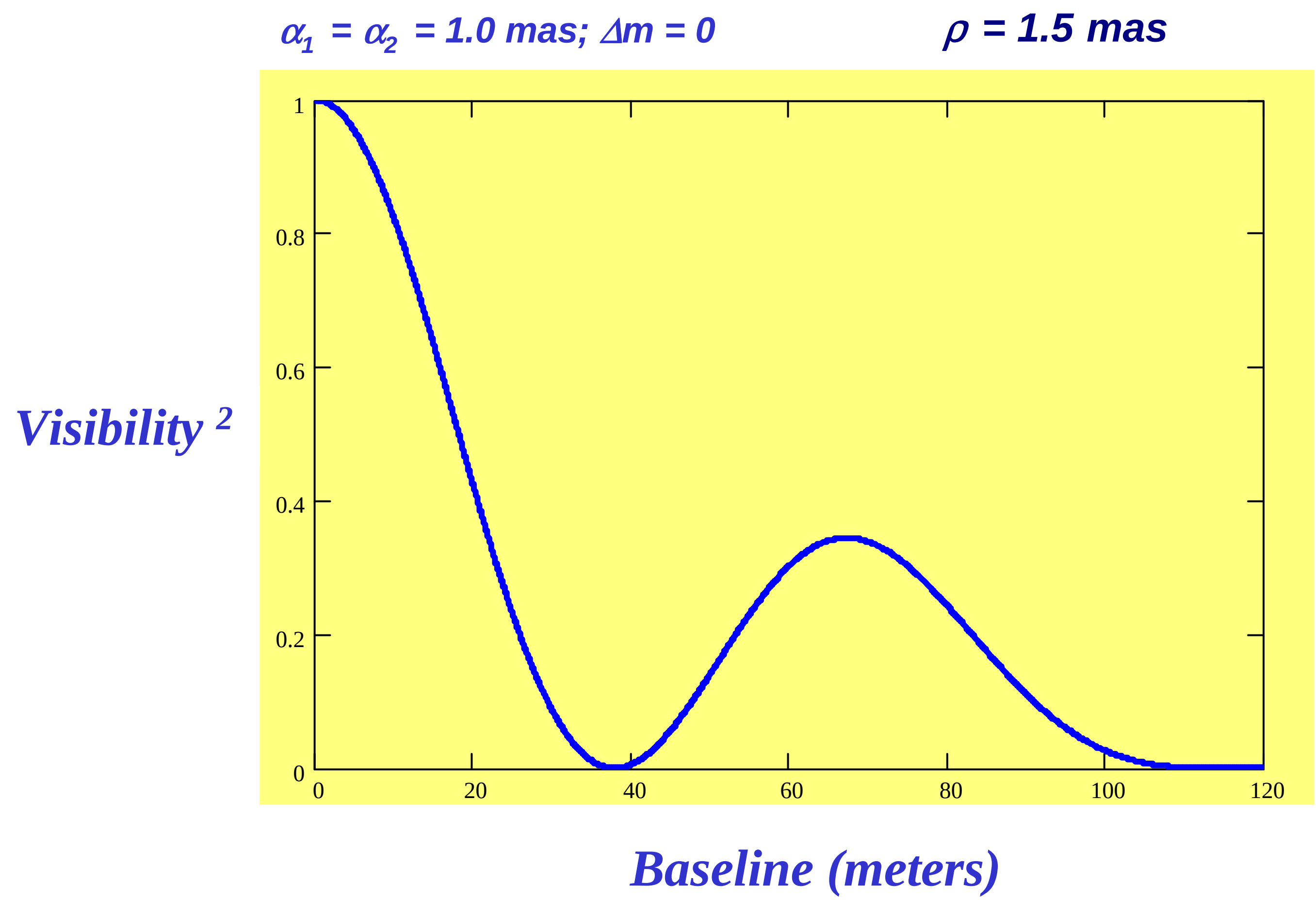
$\alpha_1 = \alpha_2 = 1.0$ mas; $\Delta m = 0$ ***ρ = 0.75 mas***

Visibility ^{2}



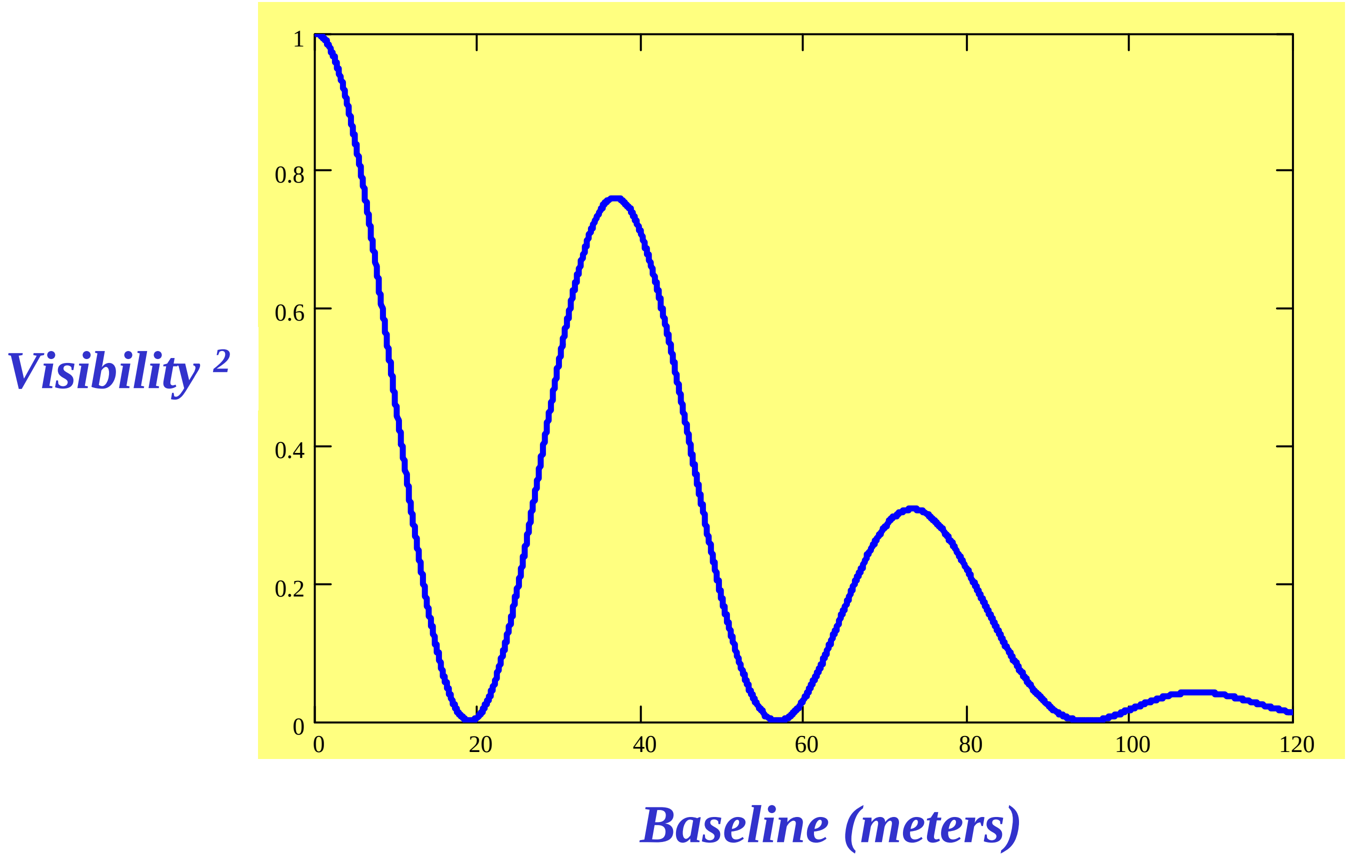
Baseline (meters)

Effect of Increasing ρ



Effect of Increasing ρ

$\alpha_1 = \alpha_2 = 1.0$ mas; $\Delta m = 0$ $\rho = 3.0$ mas

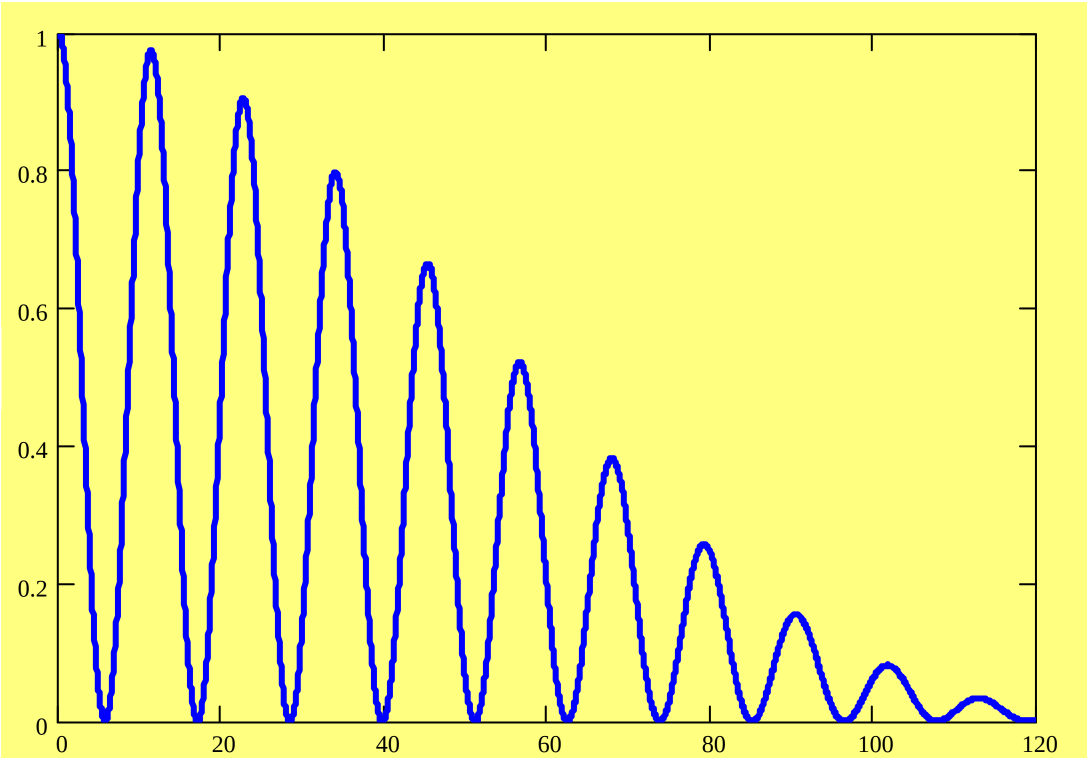


Effect of Increasing ρ

$\alpha_1 = \alpha_2 = 1.0$ mas; $\Delta m = 0$

ρ = 10 mas

Visibility ^{2}



Baseline (meters)

Challenges

- <u>**Interferometers are Complex & Hierarchical Systems**</u>

  Numerous sophisticated subsystems

  Siderostats/Telescopes

  Delay Lines

  Beam Combiners

  Alignment

  Metrology (Astrometry requires exceptional performance)

  Attention to calibration is crucial

  All working together!

Interferometry is Tough Business

Pease's 50-ft Interferometer on Mt. Wilson, c. 1935

50-ft Interferometer site in early 1980's

Challenges (Cont.)

- **Require New Tools & Algorithms**
  - *Scheduling & Archiving*
  - *Imaging*
  - *Learn from the radio experience*
- **Science**
  - *What is optimal?*
  - *What is realistic?*
  - *Over heightened expectations?*
  - *Get theorists involved*
  - *Develop collaborations*
- **Funding**
  - *Still regarded as a developmental area*
  - *Specialized near-term science (no galaxy stuff!)*
  - *Patience & perseverance*
  - *Develop Partnerships*

Opportunities

- **Wonderful Resolution**

    1,000 mas - classical imaging

    50 mas - adaptive optics

    10 mas - HST

    0.1 mas - SUSI

    2 orders gain over HST (but very narrow FOV!)

- **Access to New Science**

    Resolution and Accuracy

Opportunities (Cont.)

Current Projects are Stepping Stones to an OVLA

- **Prerequisites**
  - ***Significant science must be forthcoming***
  - ***Imaging must be demonstrated***
  - ***Partnerships must be established***
  - ***More black-belt interferometrists needed***

- **May be built in the 2010 decade??**

- **Learn from the radio experience**

  $T_{VLA} - T_{GBI}$ = ***Only ~20 years!***

Interferometry Science
Most Favorable Areas

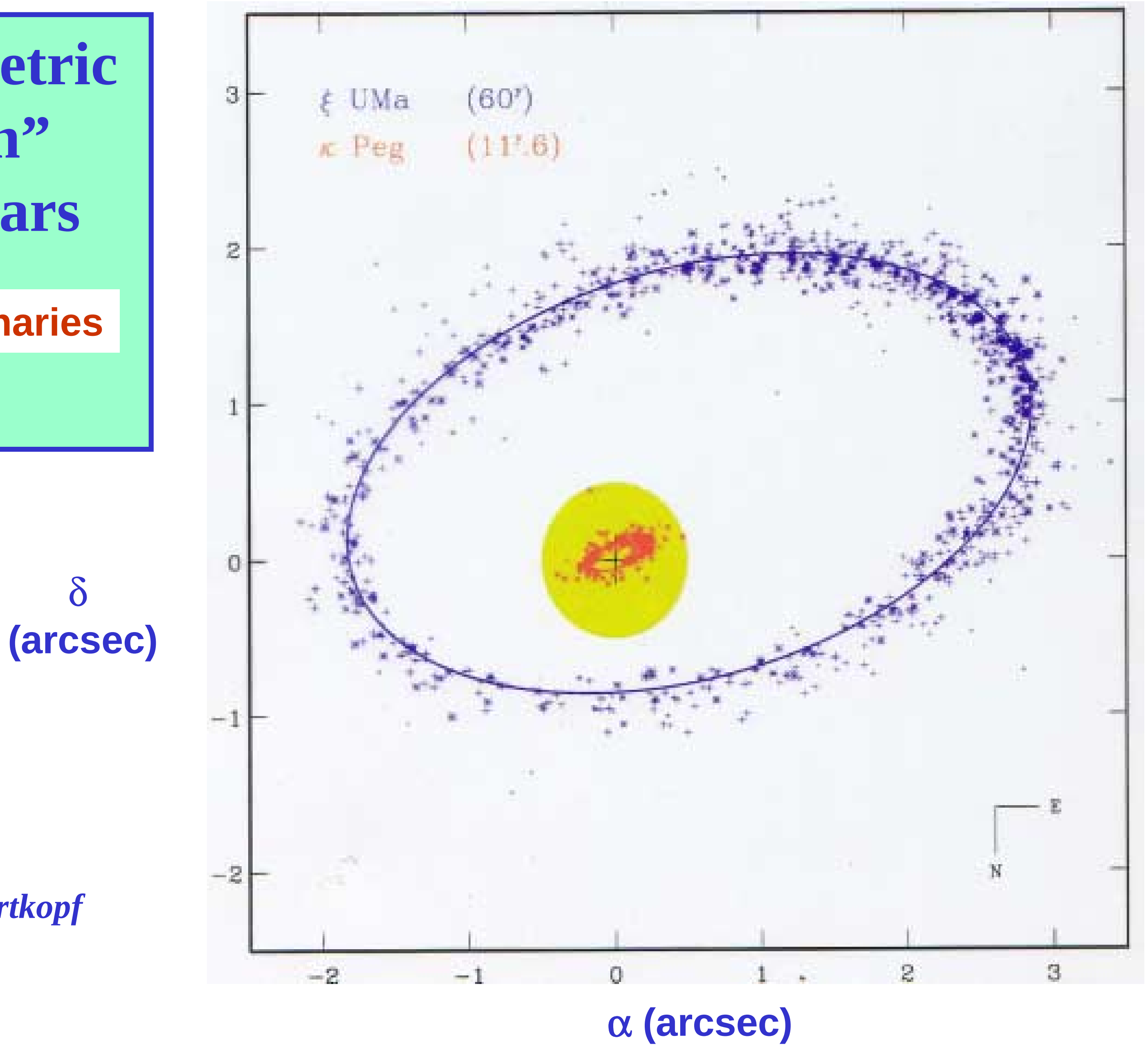
- **Single Stars**
  - Effective Temperatures & Fluxes
  - Young Stars' Structure & Morphology
  - Stellar Surface Features
  - Novae/Supernovae
- **Binary & Multiple Stars**
  - Resolved Spectroscopic Binaries
    - *Stellar Masses and Luminosities*
    - *Distance Calibrations*
    - *Radii of Components*
  - Detection of Low-Mass Companions
- **Astrometry**
  - Ground (NPOI) & Space (SIM)

Nice Example of a Revolution
Resolved Spectroscopic Binaries

- **Double-Lined Binaries**
  - Spectroscopy gives mass ratio & $a \sin i$
  - Interferometry gives a and i
  - Together yield masses & distances
    - *("orbital parallax")*
  - ~200 DSB's have a'' > 1 mas
- **Single-Lined Binaries**
  - Accurate parallaxes give individual masses
    - *Hipparcos, FAME, SIM, etc.*
- **70% of SB's are Resolvable**

An Interferometric "Zooming-in" on Binary Stars

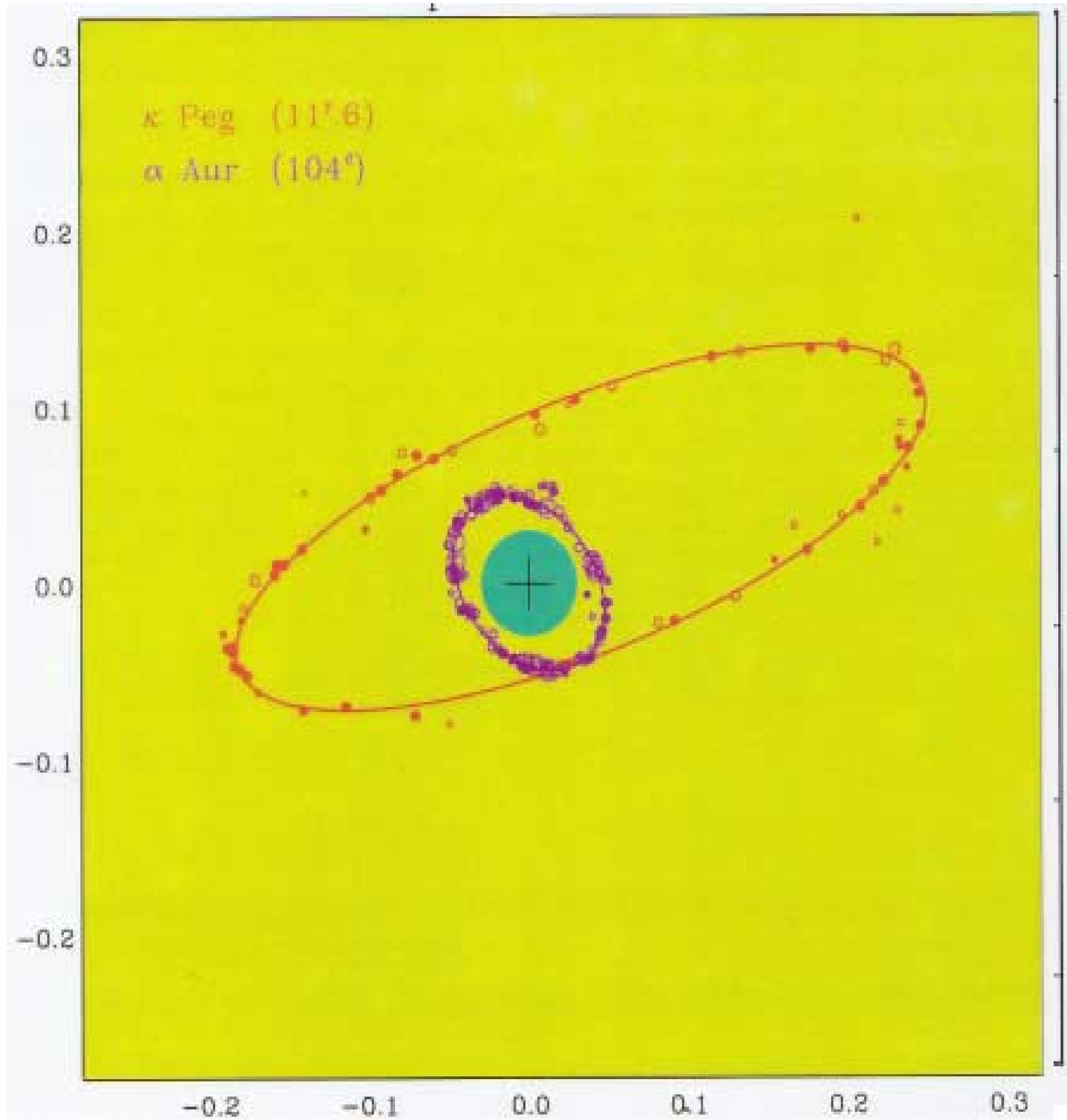
Long-Baseline Binaries



Compliments of Bill Hartkopf

An Interferometric "Zooming-in" on Binary Stars

Long-Baseline Binaries



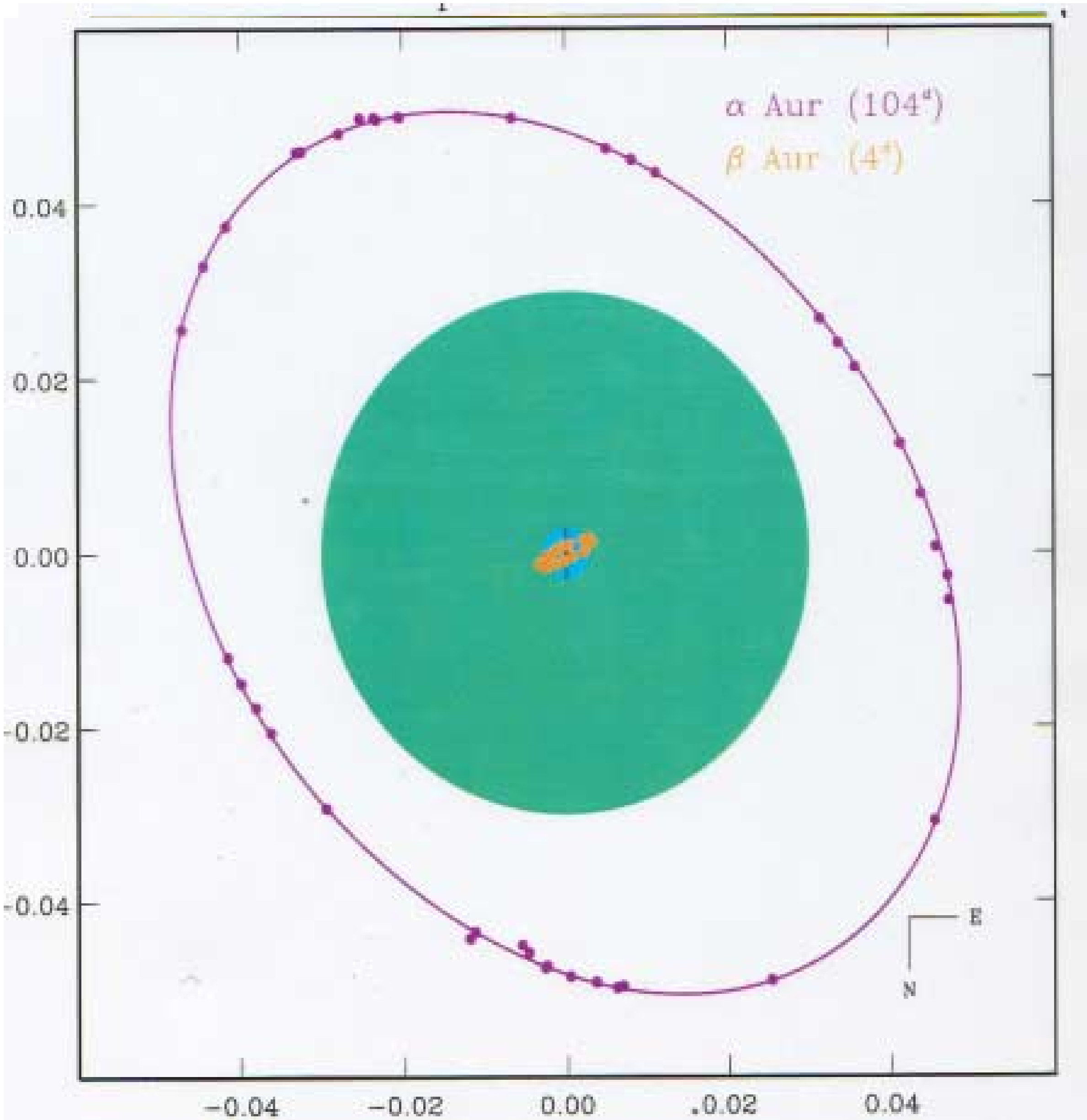
δ (arcsec)

α (arcsec)

Compliments of Bill Hartkopf

An Interferometric "Zooming-in" on Binary Stars

Long-Baseline Binaries



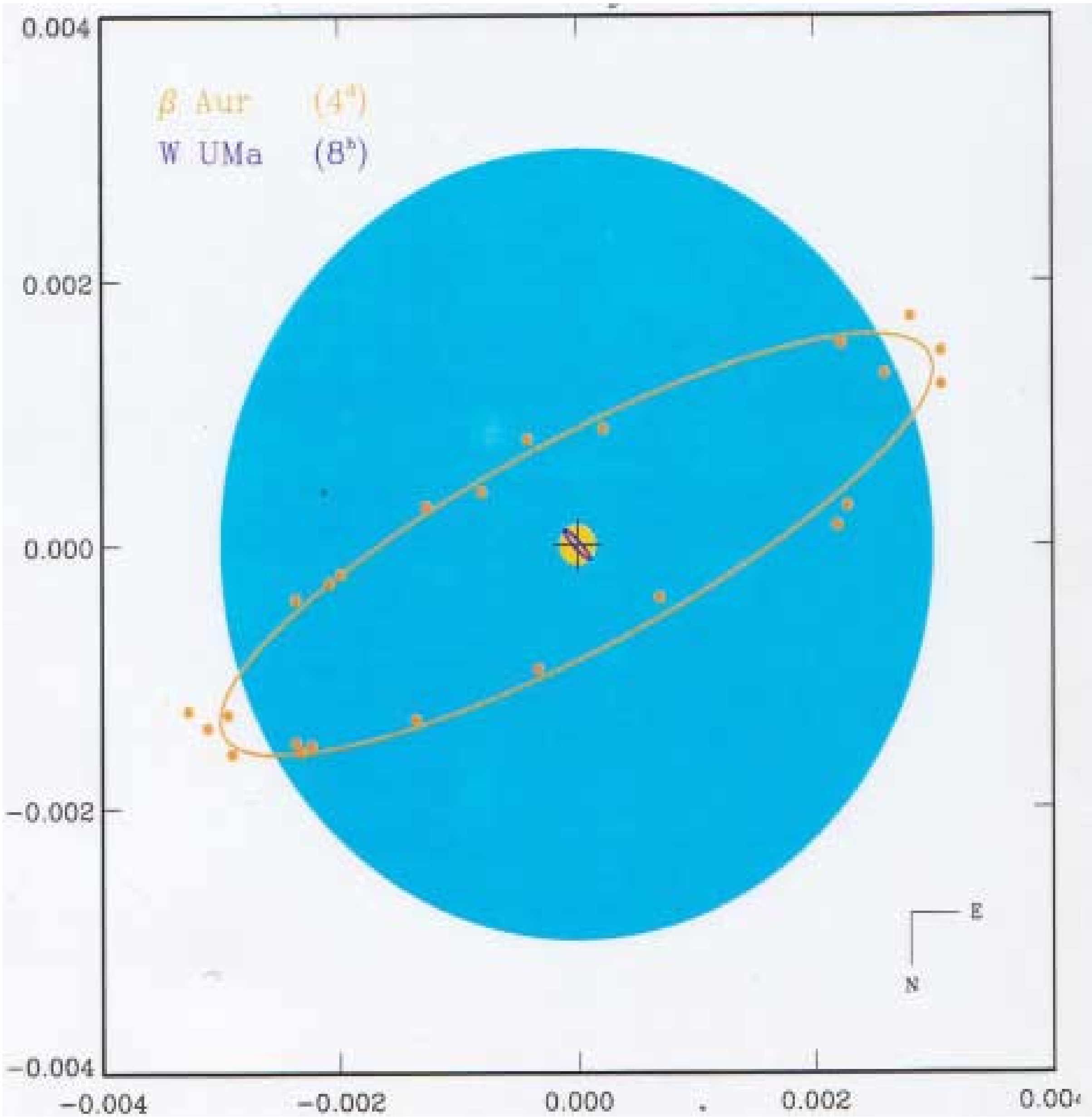
δ (arcsec)

α (arcsec)

Compliments of Bill Hartkopf

An Interferometric “Zooming-in” on Binary Stars

Long-Baseline Binaries



δ (arcsec)

α (arcsec)

Compliments of Bill Hartkopf

Interferometry Science
Other Areas

- **Single Stars**
  - Limb Darkening
  - Linear Diameters
  - Star Formation Phenomena & Dynamics
  - Pre-Main Sequence Objects
  - Absolute Rotation
  - Flare Star Phenomena
  - Cepheid P-L Calibration
  - Mira Pulsations
  - P-Mode Oscillations
  - Hot Star Phenomena (shells, winds, etc.)
  - Cool Star Shells
- **Binary & Multiple Stars**
  - Duplicity Surveys
  - Close Binary Phenomena
- **Star Clusters**
  - Proper Motions
  - Duplicity Surveys
- **Extragalactic**
  - Binaries in Magellanic Clouds
  - AGN Structure
- **Solar System**
  - Planetary Satellites
  - Minor Planets & Comets
  - Solar Surface
- **Extrasolar Planets**
  - Imaging exo-zodiacal dust
  - Astrometric Detection
  - Inspection/Verification

Interferometry Science
Other Areas (Cont.)

- **You'll Think of Something**

(Get the theorists involved!)

> ***"History has taught us that whenever a new technique enters a new realm of observational phase space, the most striking and productive results tend to those not anticipated by even the most prescient thinkers"***
>
> **- Daniel Popper, 1990**

Interferometry Science
In Perspective

- **Presently Sensitivity & (U,V) Limited**
  - **Low Throughput is Inevitable**
  - **Adaptive Optics May Help**
  - **Limited Imaging Capability**
- **Stellar Stellar Science**
- **Little or No Extragalactic Science**
  - **Limited by Sensitivity & Resolution**

Currently Operating Instruments

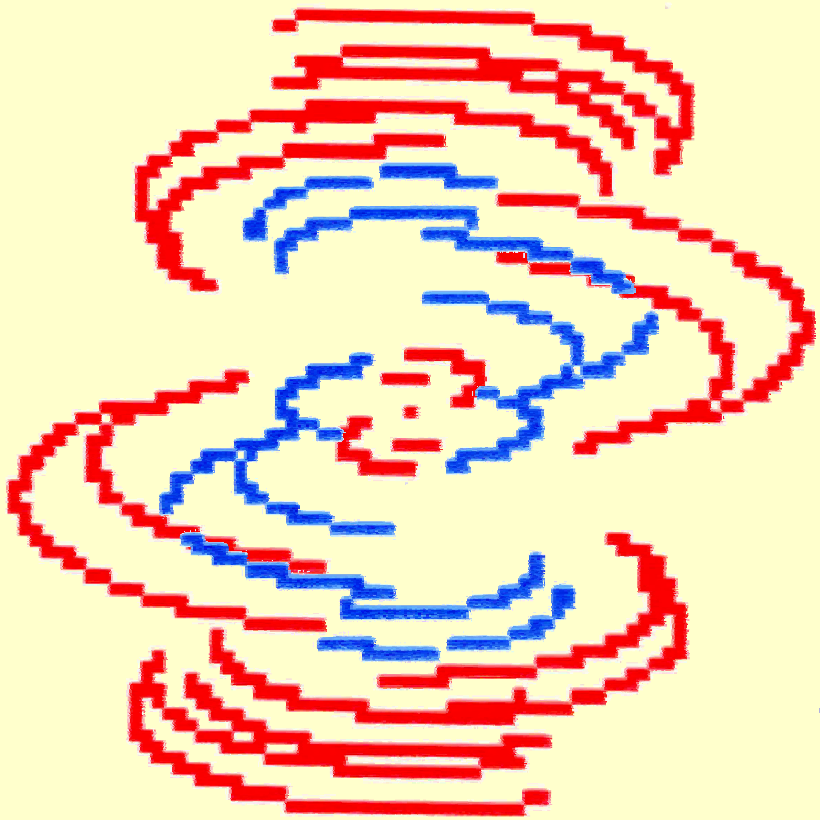
Name	Institution	Site	Number of Elements	Element Aperture (cm)	Max. Baseline (m)	Operating Wavelength (microns)	Operating Status
GI2T	CERGA	Calern	2	150	35	0.4 - 0.8 & >1.2	since 1985
COAST	Cambridge U	Cambridge	4	40	100	0.4 - 0.95 & 2.2	since 1991
SUSI	Sydney U	Narrabri	13	14	640	0.4 - 0.66	since 1991
IOTA	CfA	Mt. Hopkins	3	45	38	0.5 - 2.2	since 1993
ISI	Berkeley U	Mt. Wilson	3	165	30(+)	10	since 1990
NPOI	USNO/NRL	Anderson Mesa	6	60	435	0.45 - 0.85	since 1995
PTI	JPL/Caltech	Mt. Palomar	2	40	110	1.5 - 2.4	since 1995
CHARA	Georgia St. U	Mt. Wilson	6	100	350	0.45 - 2.4	since 1999
Keck	CARA	Mauna Kea	2(4)	1,000(150)	165	2.2 - 10	fringes 03/01
VLTI	ESO	Cerro Paranal	4(3)	840(250)	200	0.45-12	fringes 03/01

Example Walkthrough: The CHARA Array

- Located on Mt. Wilson, California
- Y-shaped Array Configuration
  - 350-meter maximum baseline
  - 2-dimensional (U,V) coverage
  - Baselines extendable to >500 meters
- Six Collecting Telescopes
  - 1-meter apertures
  - Alt/Az mounts
  - Active tip/tilt at secondaries
  - Facility can accommodate 2 more telescopes
- Evacuated Light Pipes
- Active Path Length Equalization & Fringe Tracking
- Dual Wavelength Regimes
  - 500 – 800 nm (200 μas limiting resolution)
  - 2.0 – 2.4 μm (1 mas limiting resolution)

Mt. Wilson – October 2000

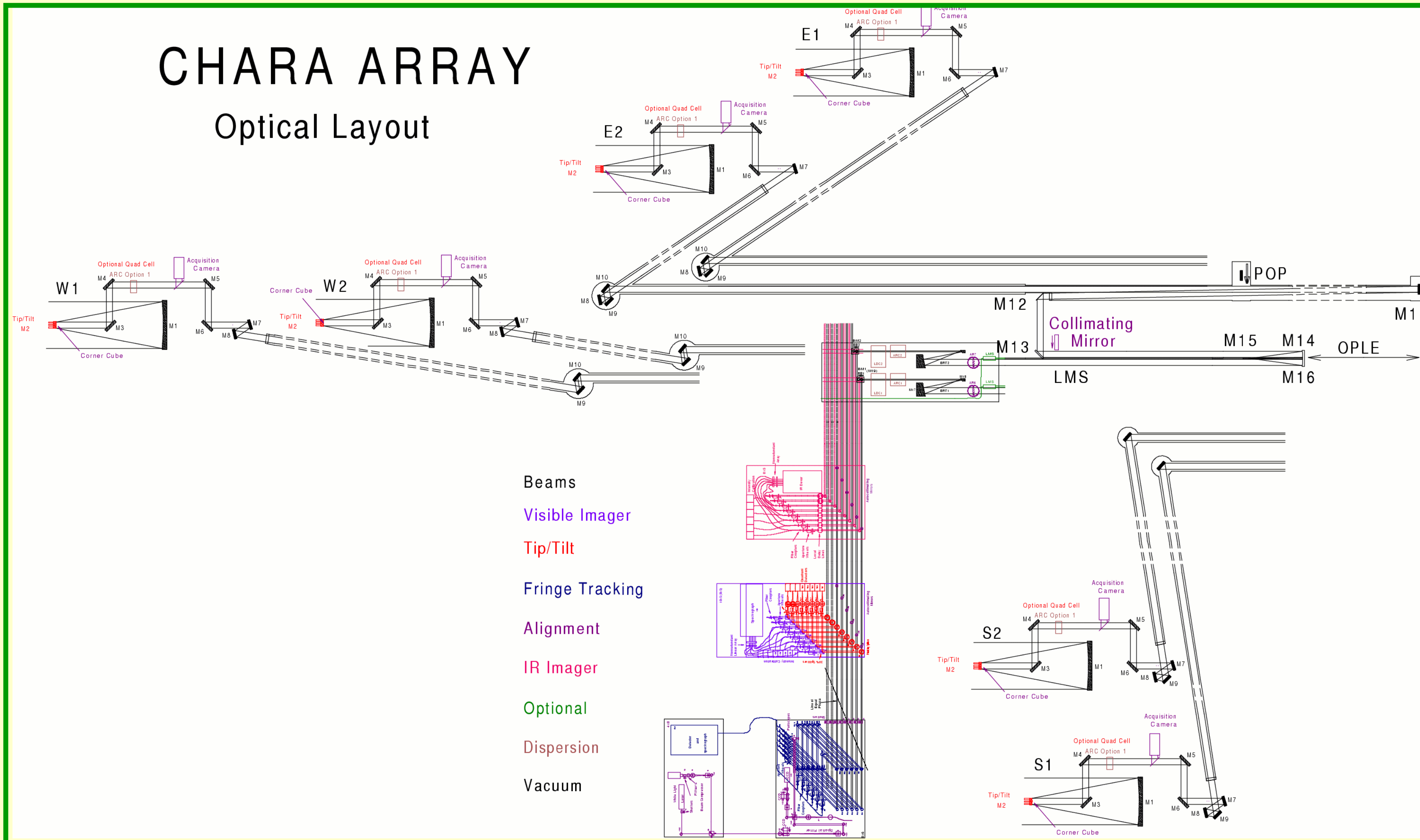
(U,V)-Plane Coverage



Original from 5-telescopes

Additional from Sixth (“Keck”) telescope

Overall Optical Layout

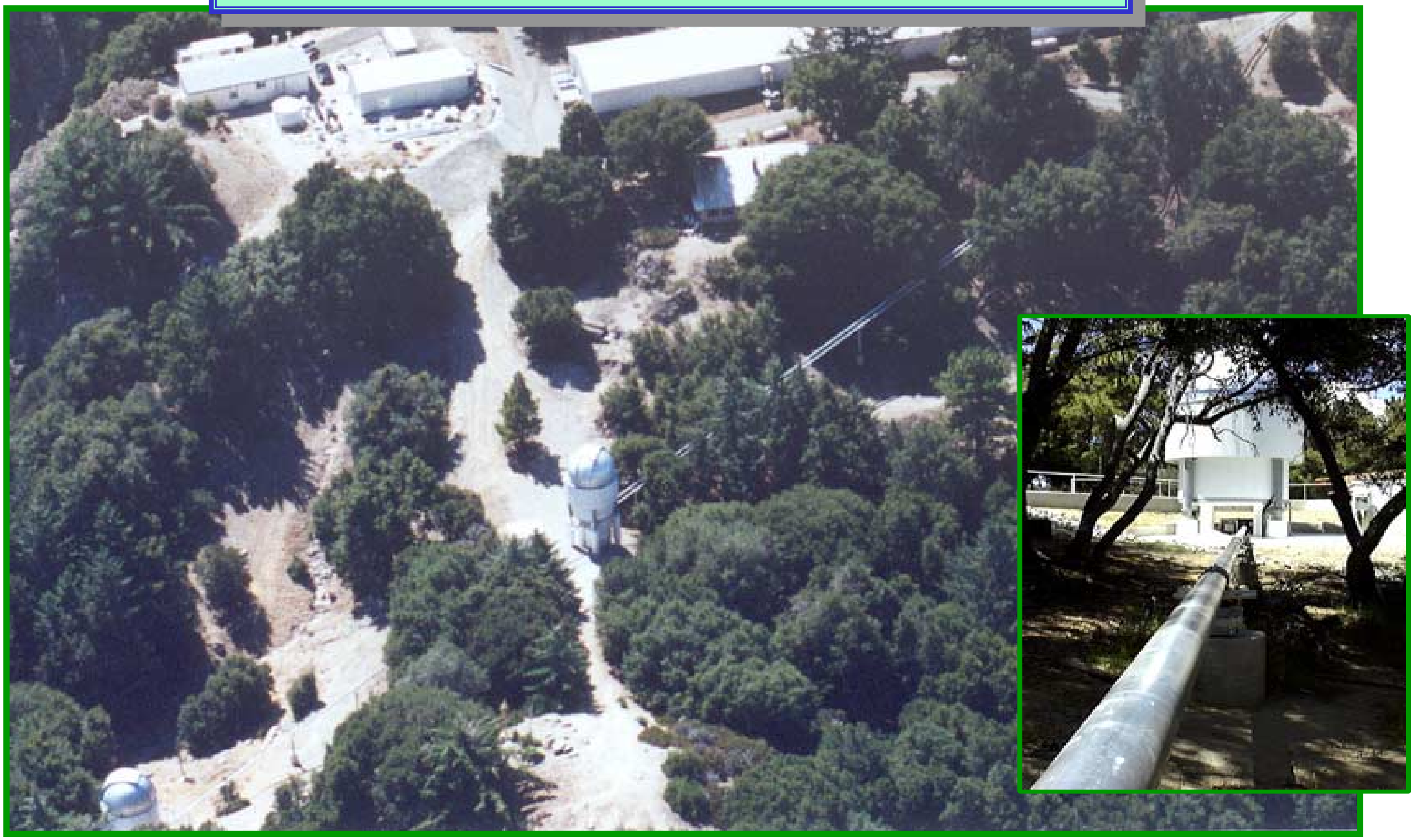


Telescope Mounts

Alt-Az with Tip/Tilt Secondaries

- 7-Reflection Design by Larry Barr
- Fabrication by M3 Engineering
- All six installed by January 2000

Vacuum Light Tubes



Vacuum Turning Boxes

From East and
West Arms

From South Arm

DC Components of Delay

The "Pipes of Pan"

Inside OPLE Area

Extension beyond OPLE Area

Exiting the PoP & Vacuum Systems

PoP End Boxes anchored to floor

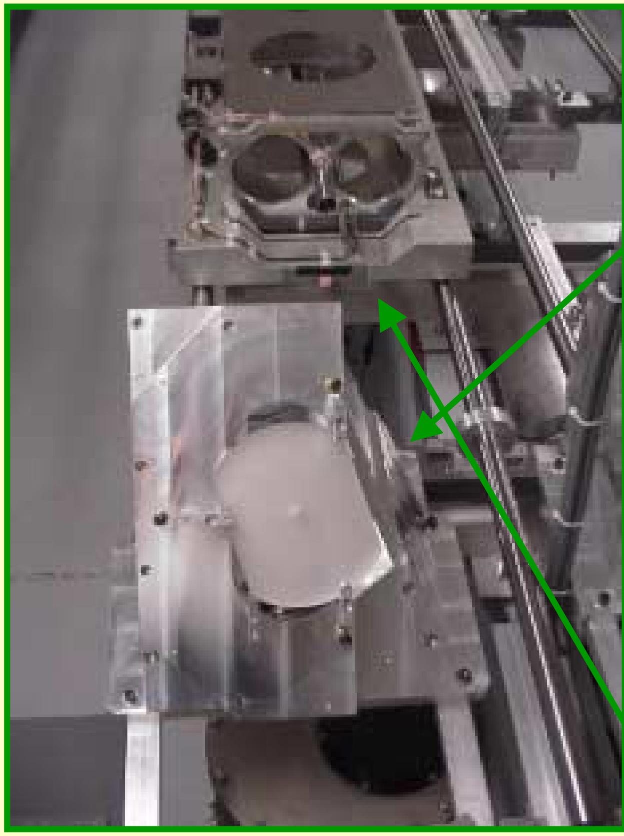
Upper periscope mirror for injection

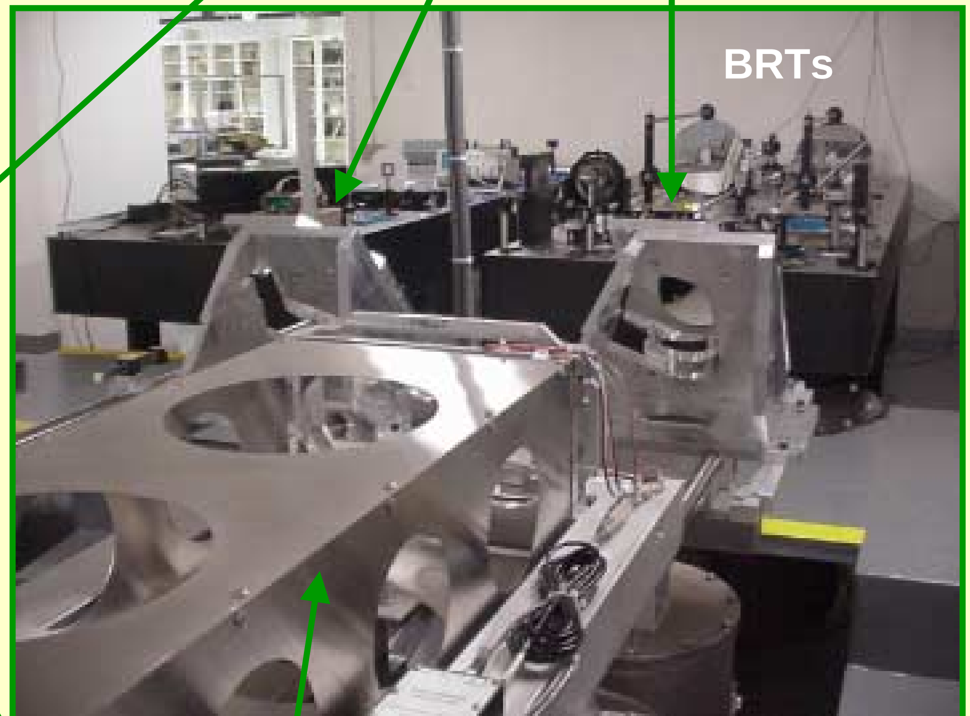
into OPLE

PoP exit via lower periscope mirror

and window

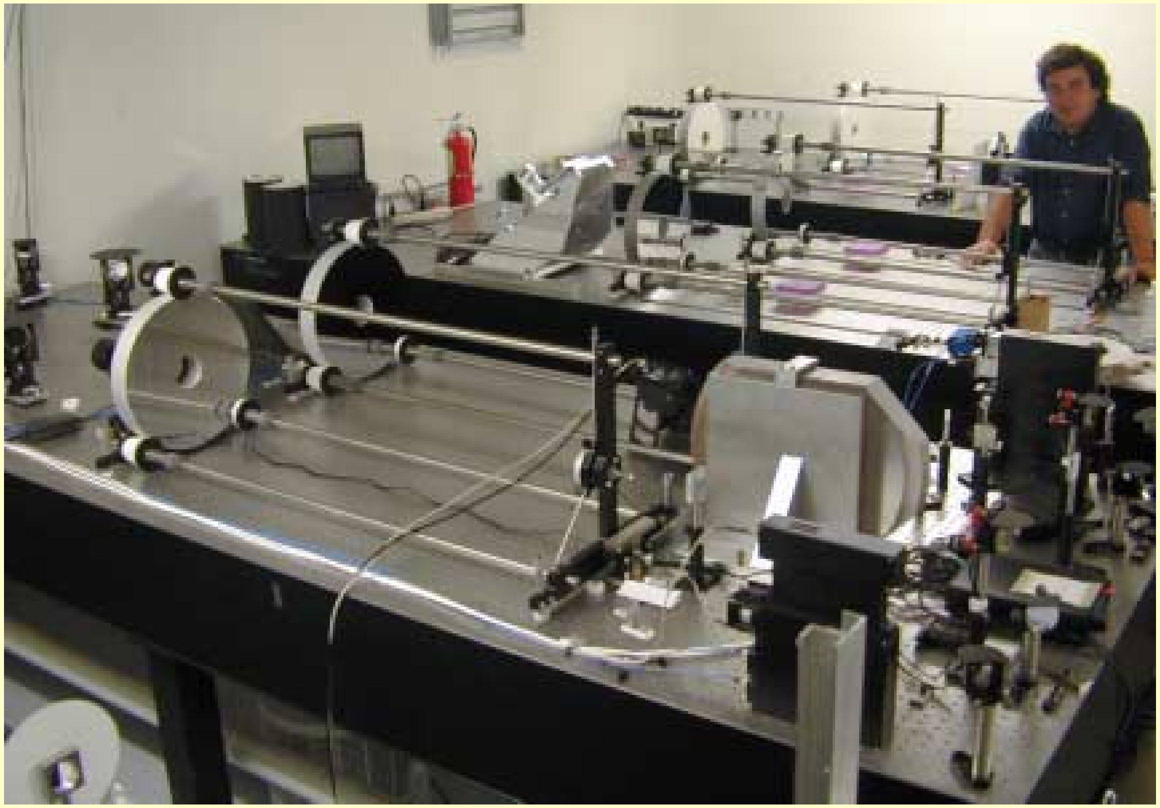
Optical Path Length Equalizers (OPLE)





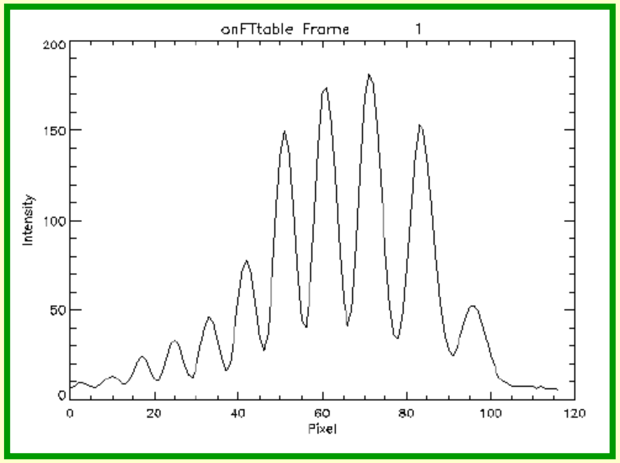
Beam Reducing Telescopes

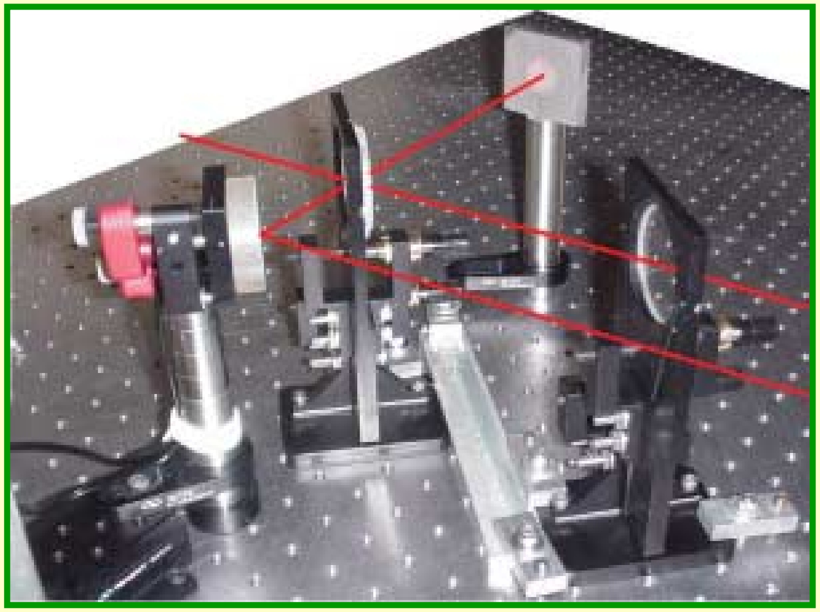
- All six BRTs built and assembled.
- Internal alignment of all six complete.
- Two BRTs installed and aligned with OPLES.



Visible Beam Combiner

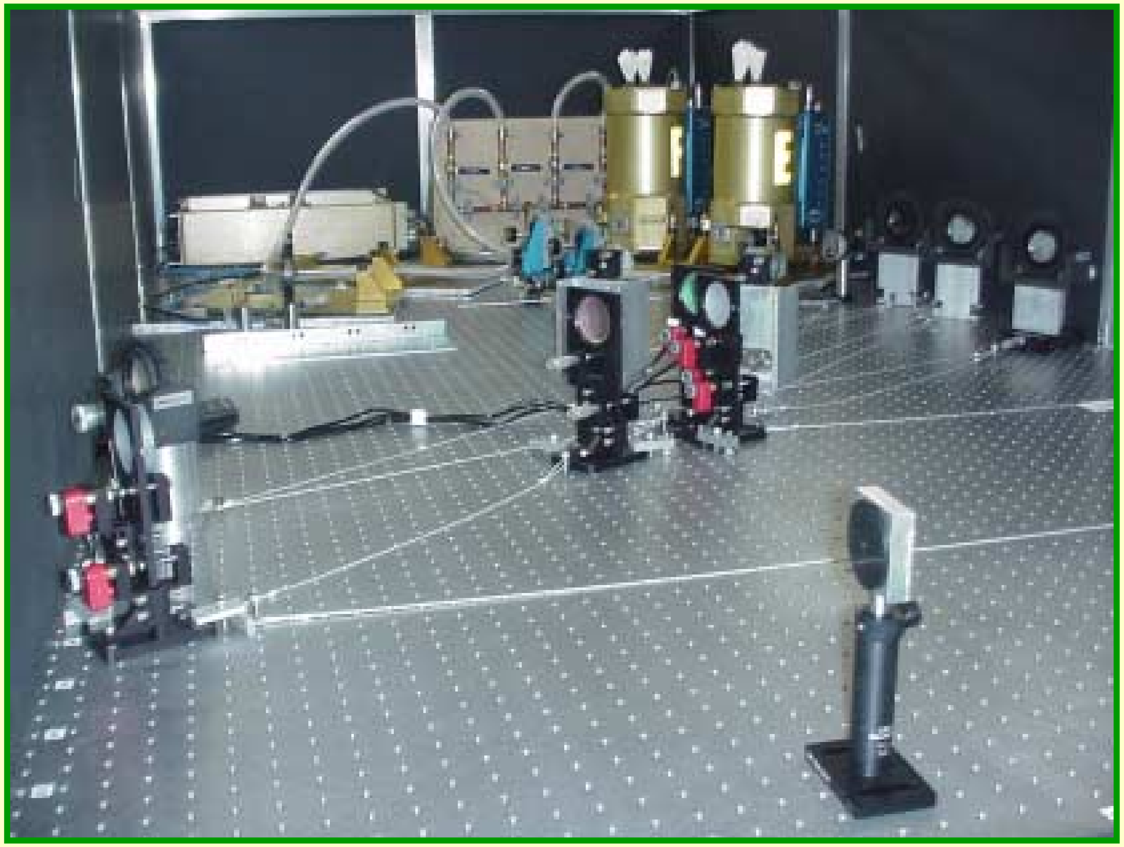
- Prototype two beam system complete.
- Primarily used for internal alignments.
- Internal visibility very high.
- Will have visible fringes on sky later this year.

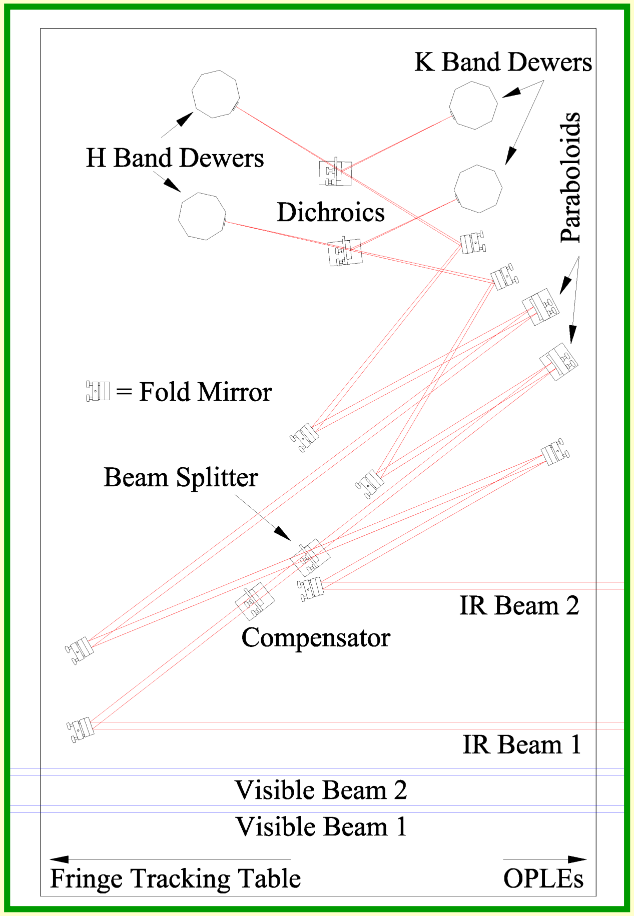




K/H Bands Beam Combiner

- Two beam H/K system in routine operation.
- Currently detector limited - new array detector this summer





K/H Band Beam Combiner Dither Mirror

Michelson's Stellar Interferometer

On Display on Mt. Wilson